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Vibroacoustic response of residential housing due to sonic boom exposure: a summary of two field tests

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ABSTRACT

Two experiments have been performed to measure the vibroacoustic response of houses exposed to sonic booms. In 2006, an old home in the base housing area of Edwards Air Force Base, built around 1960 and demolished in 2007, was instrumented with 288 transducers. During a 2007 follow-on test, a newer home in the base housing area, built in 1997, was instrumented with 112 transducers. For each experiment, accelerometers were placed on walls, windows and ceilings in bedrooms of the house to measure the vibration response of the structure. Microphones were placed outside and inside the house to measure the excitation field and resulting interior sound field. The vibroacoustic response of each house was measured for sonic boom amplitudes spanning from 2.4 to 96 Pa (0.05 to 2 lb_f/ft^2). The boom amplitudes were systematically varied using a unique dive maneuver of an F/A-18 airplane. In total, the database for both houses contains vibroacoustic response data for 154 sonic booms. In addition, several tests were performed with mechanical shaker excitation of the structure to characterize the forced response of the houses. The purpose of this paper is to summarize all the data from these experiments that are available to the research community, and to compare and contrast the vibroacoustic behavior of these two dissimilar houses.

1. INTRODUCTION

Civilian supersonic flight over land is restricted in part due to the environmental impact of sonic booms on populations over which the aircraft would fly. These restrictions were put in place based on research performed in the 1960's which studied boom intrusiveness caused by conventional supersonic aircraft designs that produce overpressures on the ground in the range of 48 Pa (1 lb_f/ft^2) or more during straight and level flight. The noise produced on the ground by sonic booms, characterized by a classic N shaped pressure signature with a high overpressure and fast rise time, was found to be sufficiently intrusive to warrant these blanket restrictions. However, there is currently a desire among airplane manufacturers to design, build, and market small jets capable of supersonic flight over land using advanced technology to mitigate boom intrusiveness. This goal has been motivated in part by the demonstration of sonic boom shaping by DARPA, NASA, and industrial partners during a recent experiment [1]. In that experiment, it was shown that the peak overpressure of a sonic boom could be reduced in a predictable way by shaping the airframe. By shaping future aircraft to modify the shock structure, several airframe

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builders are pursuing novel designs of small aircraft that should result in sonic booms with significantly lower overpressures and slower rise times than those produced by current supersonic aircraft. As a result of the lower overpressures observed on the ground, there is hope that these designs could be capable of flying supersonically over populated land without creating objectionable noise.

However, supersonic flight over land will only be possible after removal or modification of restrictions that are currently in place. Such modifications will require substantial justification that boom signatures generated on the ground by low boom aircraft are not objectionable to citizens. To evaluate the effects of low amplitude sonic booms on populations, and ultimately affect decisions regarding supersonic flight restrictions, knowledge and high fidelity tools need to be developed to enable a systematic study of the audible noise generated by low overpressure booms. Consequently, NASA has embarked on a research program to study the intrusiveness of low amplitude sonic booms heard on the ground and, in particular, inside residential houses. A portion of this NASA effort is focused on developing and validating modeling tools that can be used to study the acoustic response inside residential structures over the entire audible frequency range. Previous research, summarized in reference [2], has studied the response of buildings exposed to sonic booms. These have pointed to transmission of the boom through the structure and contact induced noises, such as rattle, as the primary sources of audible noise inside buildings exposed to sonic booms. However, most of these studies have focused on measuring the low frequency response of buildings, and have not considered the entire audible frequency range, which is essential for studies of human response.

To acquire high fidelity data that can be used to validate the desired indoor structural acoustic modeling tools, two experiments were conducted in June 2006 [3] and July 2007 [4] by NASA personnel, industry and academic partners on two different houses. Each house was exposed to several sonic booms of varying peak overpressure, and the dynamic and acoustic response of the house was measured. During the 2006 experiment, an old house, which is described in the next section, was exposed to 112 sonic booms ranging in overpressure from approximately 2.4 to 96 Pa (0.05 to 2 lb_f/ft^2). During the 2007 follow-on experiment, a newer house, which is also described in the next section, was exposed to 42 sonic booms ranging in overpressure from approximately 4.8 to 96 Pa (0.1 to 2 lb_f/ft^2). The transducers placed in and around these houses are briefly discussed in Section 3, the tests conducted are discussed in Section 4 and some vibroacoustic responses from these two dissimilar houses are compared in Section 5.

2. HOUSE DESCRIPTION

Thorough descriptions of the houses used in these two experiments can be found in references [3] and [4]. Both houses were located in the base housing area of Edwards Air Force Base. These houses are typically occupied by military personnel; however, both houses were unoccupied during these tests. The two houses differed significantly both in age and in state of repair. The house instrumented during the 2006 experiment was built around 1960 and was generally in poor repair. The house instrumented during the 2007 follow-on test was built in 1997 using modern construction methods and materials, and was in excellent condition. A brief summary of these houses is given below.

A. Physical Description of the House Used in June 2006

The address of the house used in this experiment was 7334 Andrews Avenue, Edwards, CA. An exterior view of the house is shown in Fig. 1. The floor plan of this single story detached house is shown in Fig. 2. There are three bedrooms, one main living space, a kitchen, two bathrooms, and a detached garage (Fig. 2). One bedroom was used for a control room and contained all the signal conditioning and data acquisition equipment needed to conduct the test. Three other rooms in the house, the main living area and the two bedrooms located along the north side of the house, were instrumented with accelerometers and microphones. A total of 288 transducers were placed in and around the house [3], some of which are documented briefly in Section 3 and shown in Figs. 3 and 4.

The house was built atop a slab foundation. The exterior walls of the house consisted of 2x4 wood framing, 40-cm (16-inches) on center, with a 0.95-cm (3/8-inch) thick gypsum board interior, and 1-inch thick stucco over metal lath exterior. It is not known if there was thermal insulation in the air cavity of the walls. Most of the interior walls were constructed using 2x4 wood framing, 16-inches on center, with 0.95-cm (3/8-inch) gypsum board on the finished sides of the walls. The roof was framed with 2x6 joists, and the interior sheetrock of the vaulted ceilings in the rooms of the house was attached directly to the bottom of the roof joists. It is not known if there was thermal insulation in the air cavity formed between the roof sheathing and interior sheetrock. There were three windows in each of the bedrooms [3]. The windows in the north wall of both bedrooms were similar single, non-operable panes of glass that were sandwiched in-between a wood frame. There was one operable horizontal slider type window in each bedroom. The glazings were single, non-insulated glass panes that were held in a metal sash using a plastic gasket. These sashes were held in a metal frame that was attached to the house, where there was direct metal-on-metal contact between the sash and the frame with substantial play in this interface. This created a condition where window rattle was significant even with the slightest excitation of the windowpanes.

No furnishings were placed inside any of the instrumented rooms and the flooring in the bedrooms was hardwood. Thus, these rooms were very reverberant. However, open cell foam mattress pads were placed in the instrumented bedrooms in an attempt to decrease the reverberation times in the empty rooms. The main living area, which was instrumented, was carpeted and people were present in this room for a companion test [5]. Reverberation time measurements were made in each room [3].

B. Physical Description of the House Used in July 2007

The address of the house used in this experiment was 52 Blackbird Street, Edwards, CA. It forms one-half of a duplex, and exterior view of which is shown in Fig. 5. The floor plan of the house is shown in Fig. 6. Even though the neighboring unit was occupied during this experiment, the wall separating the two units provided sufficient acoustical isolation so there was very little, if any, increase in indoor ambient noise due to presence of the neighbor. Inside 52 Blackbird Street there were three bedrooms, two bathrooms, an attached garage, and an open living space that included a family room, living area, kitchen, and dining area. The main living area of the house was used as a control room during the experiment, and contained all the needed data acquisition and signal conditioning equipment. All three bedrooms in the house (Fig. 6) were instrumented with accelerometers and microphones. A total of 112 transducers were placed in and around the house (Fig. 7) and are documented briefly in Section 3. Complete documentation can be found in reference [4].

The house was built atop a slab foundation. The exterior walls of the house consisted of 2x6 wood framing, 16-inches on center, with a 1.27-cm (1/2-inch) thick gypsum board interior, 1-inch thick stucco and metal lath over plywood exterior, with R-19 thermal insulation in the air cavity. Most of the interior walls were constructed using 2x4 wood framing, 40-cm (16-inches) on center, with 1.27-cm (1/2-inch) gypsum board on the finished sides of the wall, and 8.9 cm (3.5-inch) thick bats of acoustical insulation in the air cavity. The roof was pre-manufactured truss framed, plywood sheathed, and finished with fiberglass shingles. This roof system formed an attic space above all of the rooms. R-38 fiberglass insulation bats were used in the attic above all of the rooms. Each bedroom had one window and the windows in these three bedrooms were horizontal slider windows, where each window consisted of two glazings (Fig. 8). Each glazing was a double pane insulated glass assembly. An aluminum sash held each glazing, and each sash was installed in a metal frame attached to the house. In between the sash and the frame was a pile type weather-stripping that significantly reduced the potential for direct metal-on-metal rattle at the sash-frame interface. The window in the bedroom by the front door differed from the windows in the other two bedrooms. This window had simulated muntin bars installed in-between the two insulated glass panes (Fig. 8b). These muntin bars were attached to the insulated glass spacer at the ends of each bar, but were not attached to either of the glass panes. Consequently, this lattice was free to vibrate in the gap in-between the two panes. Under even modest excitation of the insulated glass panes, these muntin bars would "slap" each pane as it oscillated back and forth, creating audible noise indoors.

No furnishings were placed inside any of the instrumented rooms, thus the rooms were fairly reverberant. However, all of the rooms in the house were carpeted, and open cell foam mattress pads were placed in the instrumented rooms in an attempt to decrease the reverberation times in the empty rooms. Reverberation time measurements were made in each room [4].

3. INSTRUMENTATON

A thorough description of the instrumentation, and the locations where they were installed in and around these two houses, is documented in references [3] and [4]. During each experiment, bedrooms in the house were instrumented with accelerometers and microphones. Accelerometers were attached to the walls, windows, and ceilings to measure the structural vibration caused by the sonic boom excitation. Microphones were placed at arbitrary locations inside each room to sample the resulting interior sound. In addition, several microphones were placed outside, surrounding the house, to characterize the excitation field and measure the diffraction of the sonic boom around the test house. All of the transducers were synchronously sampled at a rate of either 25,600 or 51,200 Hz using a 24-bit data acquisition system. The voltage time histories of each transducer were streamed to disk using a large channel count data acquisition system and these time data are available for distribution, upon request, in either binary or Matlab formats [3,4]. For illustrative purposes, the instrumentation installed in the back bedroom of the 2006 house, front bedroom of the 2006 house, and all of the bedrooms of the 2007 house are shown in Figs. 3, 4 and 7, respectively. Each dot on the drawings represents a transducer location, and the number next to the dot identifies the data acquisition channel to which the transducer was connected.

4. MEASURED RESPONSES

As was mentioned in the introduction, the house used in 2006 was exposed to 112 sonic booms and 42 booms were observed at the 2007 house. The sonic booms studied in these two tests were generated using F-18 airplanes provided by NASA Dryden Flight Research Center. The set of 154 sonic booms observed at the two test houses ranged in amplitude from approximately 2.4 to 96 Pa (0.05 to 2 lb_f/ft^2), where approximately 126 of these were considered low amplitude booms and ranged from 2.4 to 33 Pa (0.05 to 0.7 lb_f/ft^2). F-18 airplanes in straight and level flight are not capable of generating these low amplitude booms. Thus, a unique aircraft dive maneuver was used which produces low amplitude sonic booms far forward (10 to 20 miles forward) of the dive point [6,7]. Propagation over the large distance between dive point and receiver location attenuates the boom before it reaches the receiver, which in this case was the instrumented house. The amplitudes of low booms observed at the test house were systematically varied by changing the location of the aircraft dive points relative to the house. In addition to changing the amplitude of the boom observed at the test house, the incident azimuth and elevation angles are changed when the dive point is moved. These angles were measured at the houses using a Boom Amplitude and Direction Sensor (BADS) operated by NASA Dryden [7] and are available upon request. The flight path of the airplane was recorded using carrier-phase differential GPS instrumentation onboard the airplane. In addition, the 1553 aircraft bus data such as Mach number, altitude and inertial navigation system data were archived for some flights, which are available, but are subject to International Traffic in Arms Regulations (ITAR) restrictions. Ambient weather data were measured at the house and the atmospheric profile near the test site was characterized using weather balloons. These data are available upon request.

In addition to measuring the response of the house to sonic boom exposure, several types of tests were conducted to characterize the vibroacoustic response of the houses to simpler excitation mechanisms. These tests included reverberation time measurements inside the instrumented rooms, reverberation time measurements inside the attic, impulsive balloon pops inside the instrumented rooms, impulsive paper bag pops outside of the house at several positions, and shaker excitation of the walls, windows and ceilings at select points. Since these tests were performed using simple types of excitation, these characterization tests can be used as part of a model validation exercise when developing vibroacoustic prediction tools. These tests are thoroughly documented in references [3] and [4] and are not described here for brevity.

5. DISCUSSION OF INDOOR RESPONSE DATA

Obvious sources of sound inside residential houses exposed to sonic booms include linear transmission of the sonic boom through the structure and sound from rattle, creak, and squeak caused by contact induced vibration. With the large amount of the data that has been collected, a concise method was sought to characterize the structural acoustic behavior of these two houses and to identify source mechanisms and their relevant frequency ranges. Comparisons between indoor one-third-octave band sound levels and corresponding exterior sound levels and structural vibration levels were found to be useful. In Fig. 9, the sound levels in fifteen different one-third-octave bands measured inside the back bedroom of the 2006 house are compared with nearby outdoor sound levels (Fig. 9a) and vibration levels measured on the window in the room (Fig. 9b). Each data point represents the responses measured during one sonic boom.

At very low frequencies, high correlation between indoor and outdoor sound levels is observed (Fig. 9a). A Helmholtz resonance is observed below 10 Hz when the window is opened, increasing interior levels for a given exterior level (Fig. 9a, red dots). This is a result of the radiation load of the open window coupling to the acoustic stiffness of the air space inside the room. At frequencies below approximately 50 Hz, the high correlation between the interior and exterior sound pressure levels (Fig. 9a) is a result of linear transmission of the boom through the structure. The correlation begins to break down above approximately 50 Hz (Fig. 9a). However, the angles of incidence of the booms varied, and this simple comparison does not account for the effects different angles of incidence have on the ratio of indoor to outdoor sound pressure level. This reduced correlation is due to changes in the excitation field caused by diffraction of the boom around the house at frequencies when the wavelength in air becomes comparable to the size of the house. Above approximately 200 Hz, there is little correlation between the sound pressure levels measured indoors and outdoors (Fig. 9a). However, at these frequencies the indoor sound pressure level is highly correlated with the window acceleration level (Fig. 9b). This is a result of contact induced vibration, which is evident in the acceleration time history at the center of the windowpane shown in Fig. 10. At points of maximum acceleration, which correspond to points of maximum deflection of the windowpane, high frequency events that decay quickly are visible in the time history (Fig. 10, red arrows). This is rattling caused by impacts between the window sash and frame due to mechanical play in the interface (Section 2a). The low frequency oscillation that triggers these events is the 14 Hz first bending mode of the glass pane of the window. Since there is significant energy present in the sonic boom at low frequencies, the low order bending modes of the pane are excited intensely and spawn these rattle events. This rattling creates high frequency audible noise indoors (Fig. 9b). The magnitude of the rattle present in the 2006 test house was significant due to the presence of single pane windows, metal-on-metal contact at the sash-frame interface, and the general state of disrepair of the windows.

After completion of the 2006 experiment, it was concluded that a repeat test on a house of more recent construction would be a valuable second data set to help understand issues related to contact induced noise (in addition to other issues). The conclusions from the subsequent 2007 test, with respect to rattle, are aptly illustrated in Fig. 11. Acceleration time histories are shown for the master bedroom and front bedroom windows; note the different ranges on the ordinate. Very little rattle was observed in the master bedroom (Fig. 11a) of the house used in 2007 due to the tight fit of the sash in the window frame. The sound field inside this bedroom was dominated by linear transmission of the boom through the structure. However, in the front bedroom of the house used in 2007, contact between the insulated glass panes and the muntin bars produced significant rattle (Fig. 11b). The responses illustrated in Fig. 11 are for the same sonic boom.

5. CONCLUSIONS

The response of these two houses to sonic booms illustrates that a wide range of indoor sound levels can be expected, and that the response indoors is largely the result of two phenomena:

- Linear transmission of the boom through the structure at lower frequencies
- Contact sources that are excited at low frequency structural resonances, but which radiate noise at high frequency due to contact induced vibration.

In addition, diffraction of the sonic boom around the house becomes important when considering the linear transmission through the structure at higher frequencies. The transition frequency where rattle becomes important varies with the objects present in a specific house and therefore is unique to a particular home construction. Thus, bounding the levels of rattle expected over a wide cross-section of housing is difficult. NASA is currently funding an experimental and analytical effort that is quantifying the levels of window rattle that is observed in a broader cross-section of housing [8].

While the findings mentioned above are not novel [2], the high fidelity tools needed to predict the transient acoustic response inside houses due to these phenomena, and high quality validation data using low amplitude sonic boom excitation, are not readily available. Thus, the database that has been developed from these two experiments, and continuing in-house and out-of-house experimental efforts, has significantly expanded the suite of high fidelity experimental data that can be used to validate such tools. These data from the 2006 and 2007 experiments are available, upon request, to the research community. Requests should be directed to the first author or this paper. Ultimately, validated analysis tools are sought which can predict the transient acoustic response inside residential houses exposed to low amplitude sonic booms.

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[8] N. Sizov, et. al., "Measured Rattle Threshold of Residential House Windows", Proceedings of Noise-Con 2008, Dearborn, MI.

Figure 1: Photograph of the front of the house used in 2006.

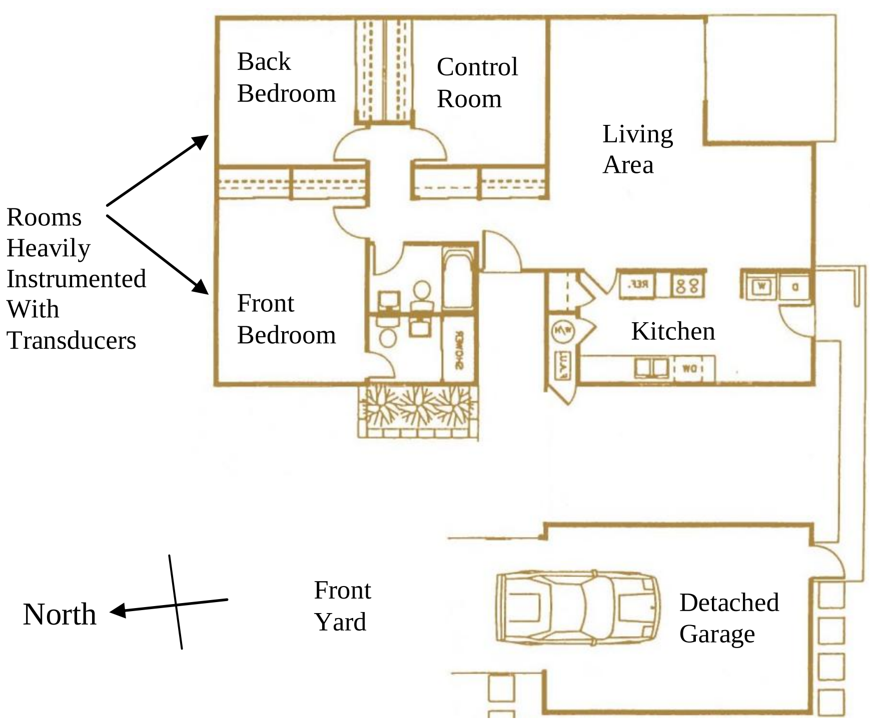

Figure 2: Floor plan of the house used in 2006 located at 7334 Andrews Avenue, Edwards, CA.

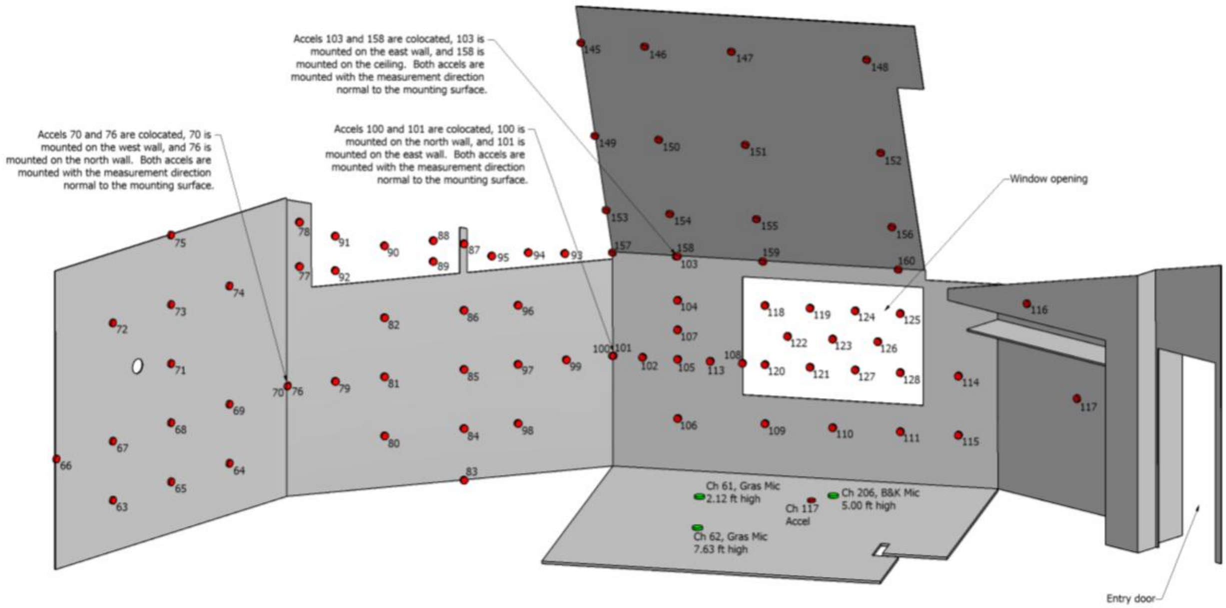

Figure 3: Transducers installed in the back bedroom of the house used in the 2006 experiment.

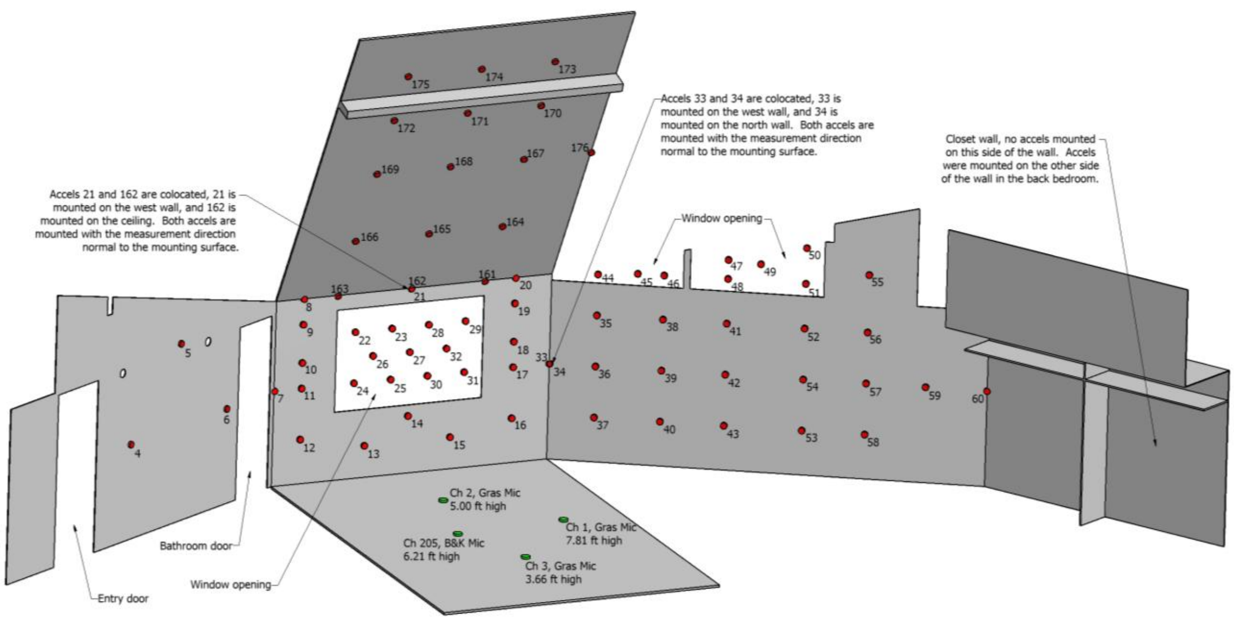

Figure 4: Transducers installed in the front bedroom of the house used in the 2006 experiment.

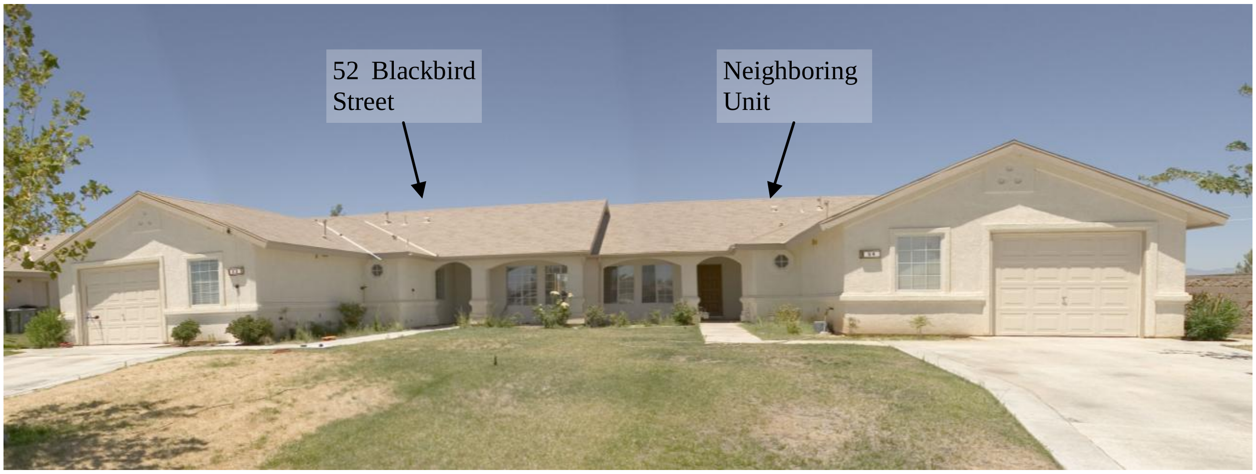

Figure 5: Front of the house used in 2007, 52 Blackbird Street is the left portion of the duplex.

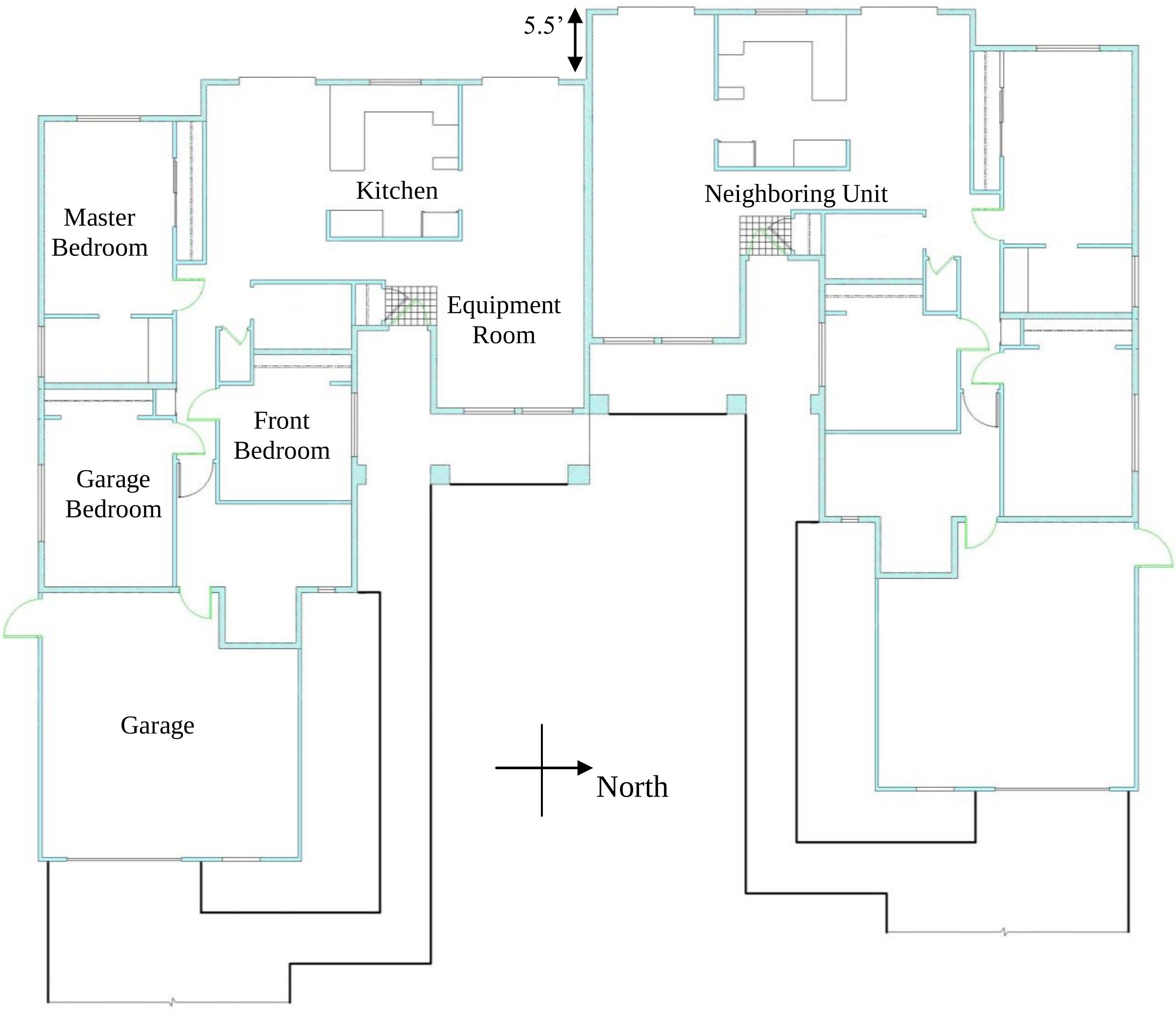

Figure 6: Floor plan of the town house at 52 Blackbird Street illustrating both sides of the house. The floor plans are mirror images of each other, offset by 0.14-meters (5.5-feet).

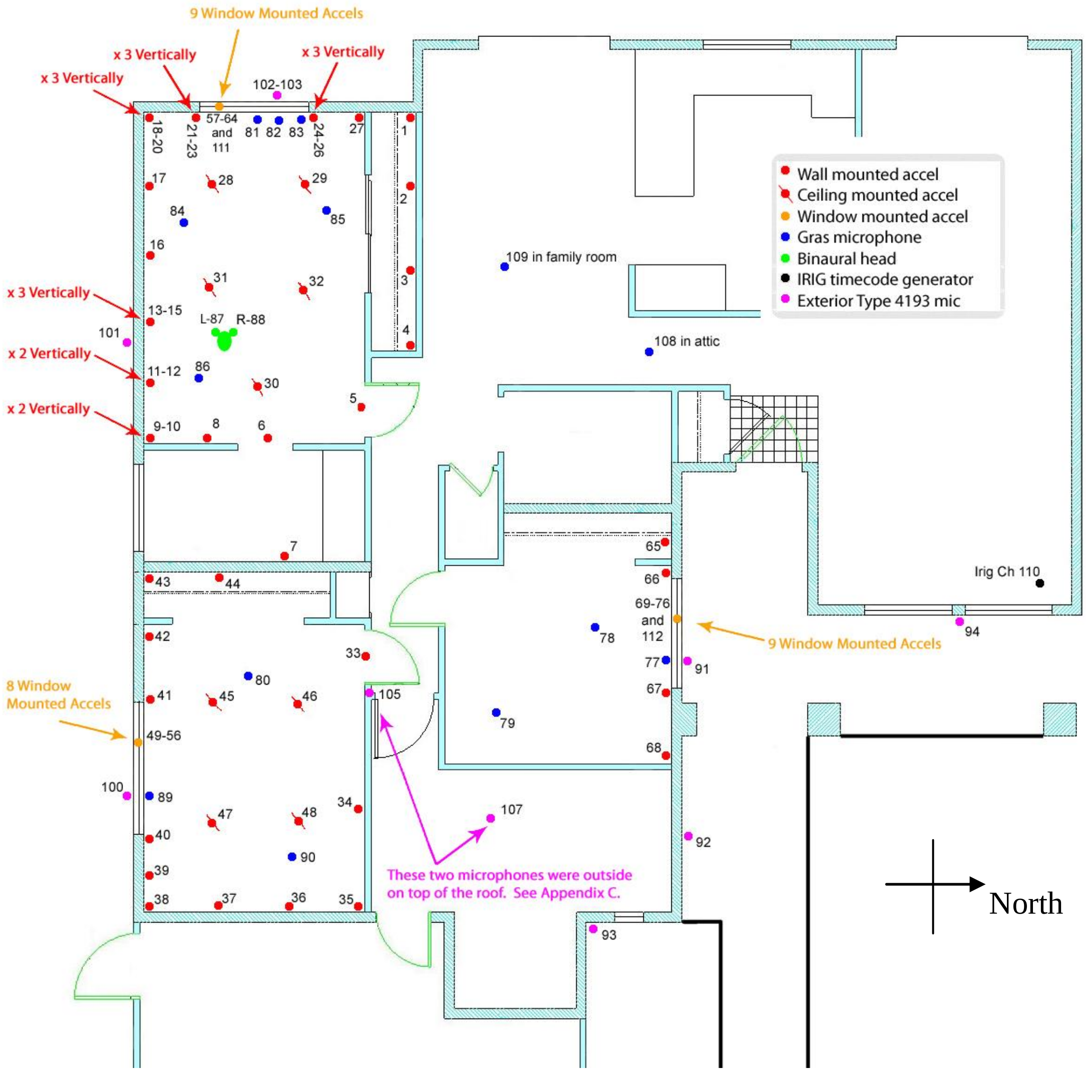

Figure 7: Partial list of the transducers installed in the house used in the 2007 experiment.

a) b)

Figure 8: Photographs of the horizontal slider windows in a) the master bedroom and b) the front bedroom of the 2007 house. The right sash of the window is operable. The left is fixed.

a) b)

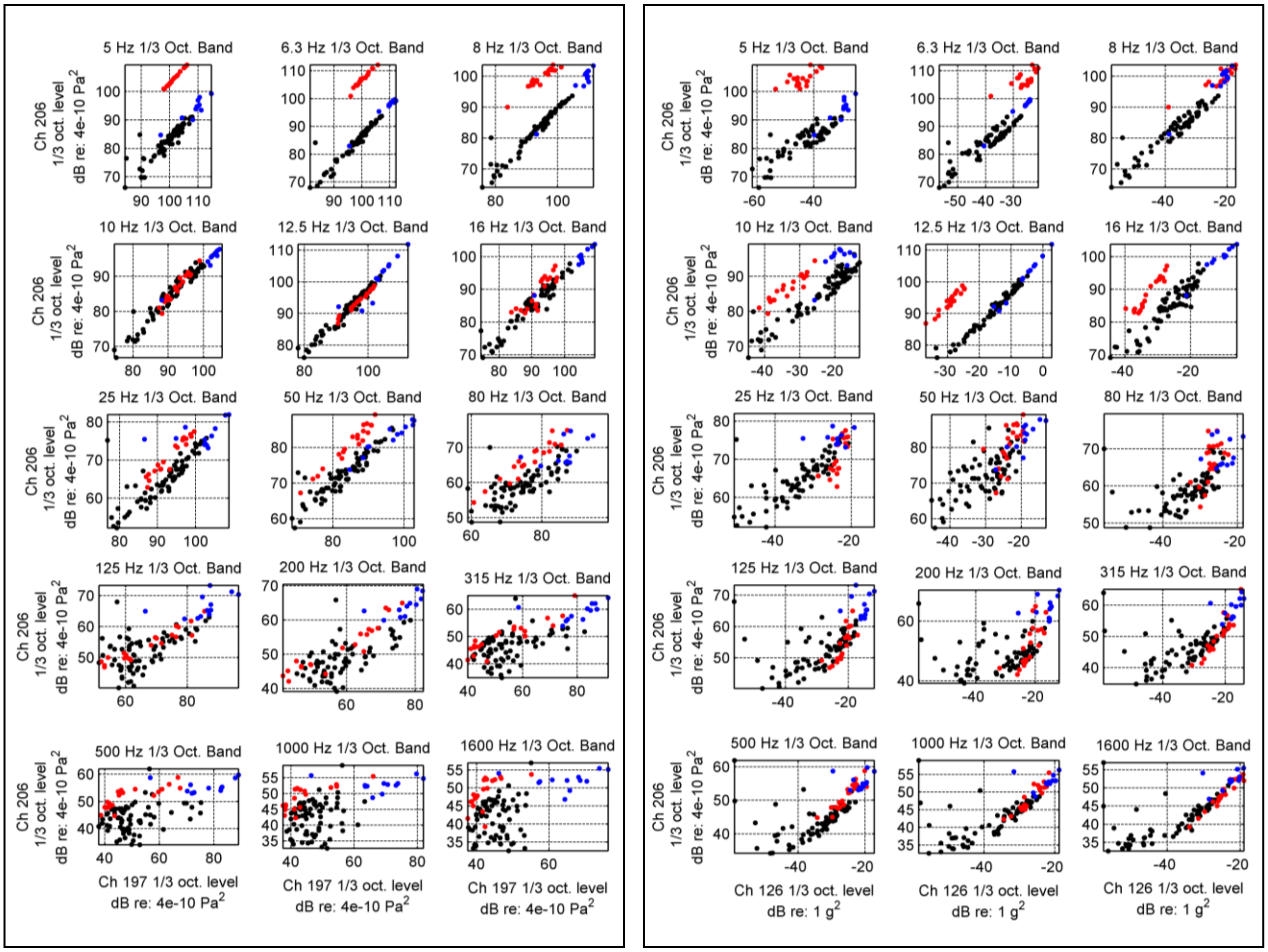

Figure 9: Excitation-response relationship between various transducers in fifteen one-third-octave bands from the 2006 test house; a) an indoor microphone response (channel 206) versus a nearby outdoor microphone response (channel 197) for all 112 booms and b) an indoor microphone response (channel 206) versus a window mounted accelerometer response (channel 126) for all 112 booms; "●" low amplitude booms with window closed; "●" low amplitude booms with window open; "●" normal amplitude booms.

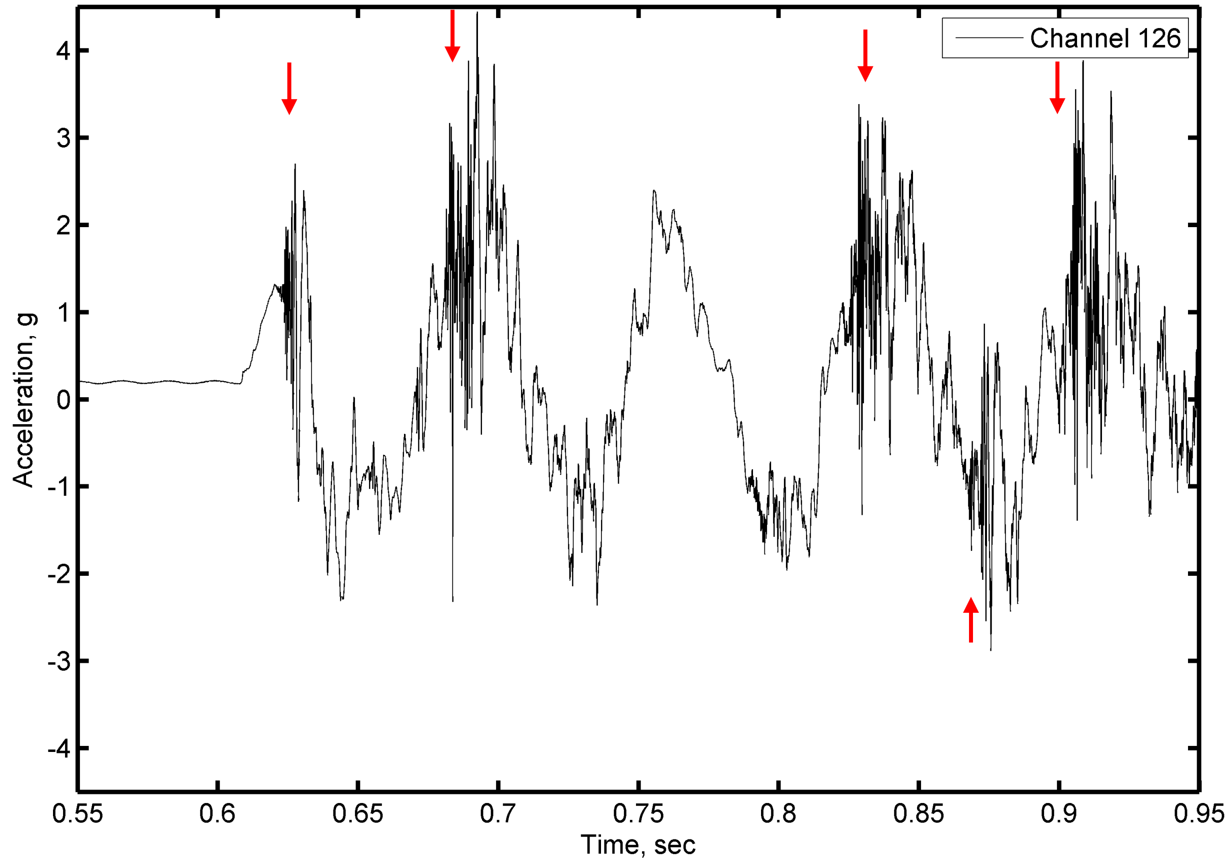

Figure 10: Time history of an accelerometer mounted to the center of the windowpane in the back bedroom of the 2006 test house. Rattle is occurring at the points of maximum acceleration as marked by ↓.

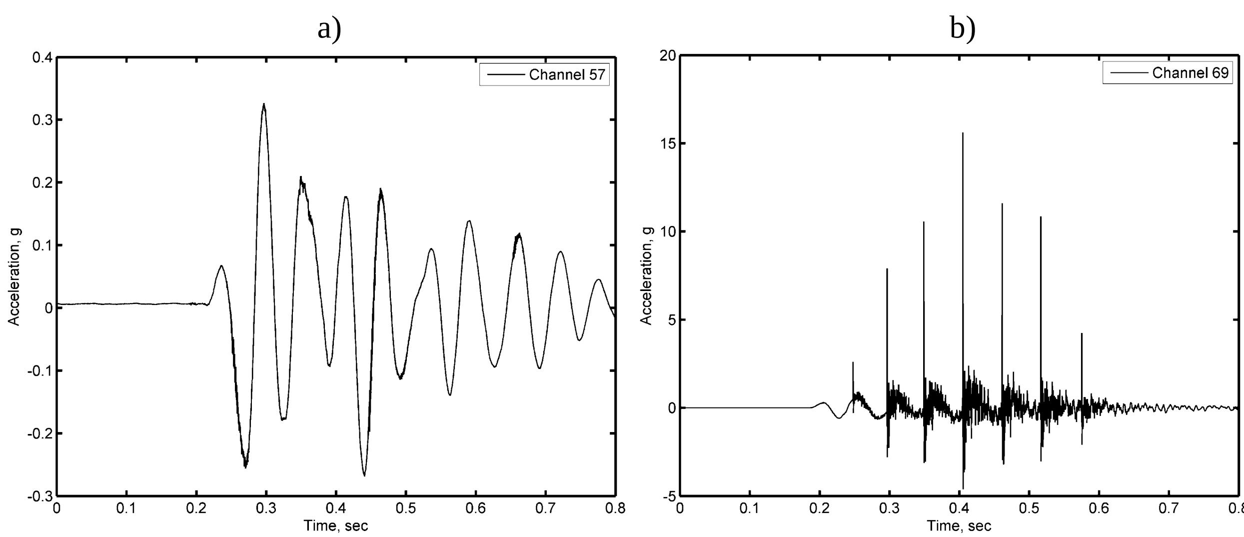

Figure 10: Time history of accelerometers mounted in the center of two windowpanes in the 2007 test house; a) the master bedroom window shown in Figure 8a and b) the front bedroom window shown in Figure 8b. The responses shown are for the same sonic boom. The contact induced vibration caused by the muntin bars of the front bedroom window is evident in b).